A Fully Automatic Method of Removing EOG Artifacts from EEG Recordings

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***Abstract*—Electroencephalogram (EEG) signal is quite weak and can be easily contaminated by electrooculogram (EOG). This makes the signal processing and analyzing quite difficult. An automatic correction method with high effectiveness is perceived as an important technique to solve this problem. In this paper, a Hilbert-Huang transform (HHT) based automatic correction method is proposed. According to the local time-frequency properties of EOG and statistical characteristics of intrinsic mode function (IMF), EOG artifacts can be removed from EEG using this method. HHT has perfect local time-frequency properties, which could adapt to EEG with non-stationary signal. The results show that this method can remove EOG artifacts automatically from EEG which is contaminated by it.**

***Keywords*—HHT; EOG; EEG**

I. INTRODUCTION

Electroencephalography EEG can reflect the activities of the nervous system, which is an important tool for analyzing the brain function. There are potential values for EEG research in brain science, rehabilitation engineering, biomedical engineering and man-machine control etc. EEG research has become a fever field in the international scientific community [1]. In China, Tsinghua University, Shanghai Jiaotong University, Chongqing University etc have begun to engage in researches in this area [2].

EEG recorded electrodes reflects the activities of lots of neurons. Because the structure of cerebral cortex is very complex, the activities of EEG are diverse, and the EEG signal is very weak and vulnerable to be influenced by the various types of interferences in the collection process, which brings great difficulties to the analysis of EEG signals. Therefore, the extraction of pure EEG signals is an important issue. The current purification methods in EEG are as follows: (1) frequency domain analysis. This method is based on Fourier transform method, which reflects the frequency domain characteristics of entire signal of all time, but can not provide the frequency information on any local time, in which the local contradiction between time domain and frequency domain exists, so this method is only used for stationary signal analysis. (2) time-frequency analysis. Time-frequency analysis method is to map the signal through a transformation from time to frequency plane approach, which can reflect the time and frequency information of signals. Therefore, this method is more suitable for non-stationary signal analysis. The main methods of time-frequency are short-time Fourier transform (STFT), wavelet transform etc. To some extent, STFT compensates for Fourier transform through adding a fixed time window on the signal width and assuming that non-stationary signal analysis window is stationary within a short time interval. For Wavelet transform, its window size (the window area) is fixed, but its shape is variable. The time-frequency localization analysis method with the alterable time window and frequency window is a one of the better time-frequency analysis method, which can solve the contradiction between time and frequency resolution. But the Wavelet Transform needs to select the transform basis function with engineering experiences, because once the fixed wavelet basis can not be changed later, it would lack adaptability [3].

Hilbert-Huang Transform (Hilbert-Huang transform, HHT) is a new time-frequency localization analysis method presented by Huang N. et al for analysing the nonlinear and non-stationary signals[4]. Based on the time scale of the signal local characteristics, it avoids the faults of the global space of Fourier transform definition when dealing with the non-stationary signal[5]; it is based on the signal, and can select the transform basis function adaptively, so it has a good adaptability; it can get good clustering performance at the time and frequency domain, and is no longer influenced by the Heisenberg uncertainty principle, therefore it is very suitable for nonlinear, non-stationary signals, while the EEG is a type of non-stationary signal, so HHT is suitable for EEG signal processing. In this paper, based on the EEG features of ocular artifacts, the removal method of ocular artifacts from EEG is proposed.

II. DATA ACQUISITION

EEG data from BCI Competition IV contest data sets is called Data sets 2b.EEG signal is acquisited as follows: according to international standards 10 - 20 systems, the electrodes are placed in the C3, C4, Cz positions, as shown in Fig. 1 (a), the amplitude range is ± 100 μV. For 3-lead synchronous acquisition of the eye signals (EOG), as shown in Fig. 1 (b), the amplitude range is ± 1 mV. The sampling frequency is 250Hz, analog filtering is 0.5 ~ 100 Hz, and the notch frequency is 50Hz. Signals are recorded at each state, including: idling, eye blinks, horizontal eye movement, vertical eye movement, eye rotation, motor imagery of left, motor imagery of right and so on.

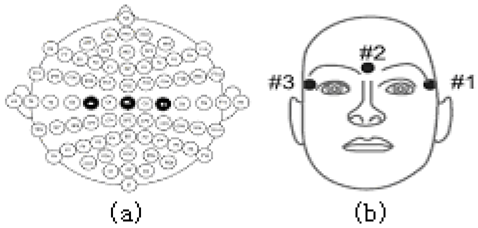

Fig. 1 Position of EEG electrodes

III. OCULAR ARTIFACTS REMOVAL

EEG signal is a kind of weak electrical physiological signal, during the collection process, it is vulnerable to be influenced by various types of interferences, which brings great difficulties for the analysis of EEG signals. Artifacts in the EEG include ocular artifacts (EOG), glossokinetic artifacts, EMG artifacts, pulse artifacts and sweating artifacts and so on. Compared with other disturbance sources, ocular artifacts is the most important component among the EEG signal interferences. It comes from the body itself, when the eye blink or move, it will cause a large potential change. EOG artifacts disperse to the entire scalp from its source, its amplitude can reach 100 mV, while the EEG amplitude is very weak with only 50μV, therefore it can make the collected EEG signals obviously distorted. Meanwhile, the band of EOG voveres the band of EEG, which causes great difficulties in the analysis of EEG signal. During the experiment, subjects' eye blinking and movement are random, and it is difficult to avoid eye blinking and movements for a long time. Therefore, the study about EOG removal method is an important content in preprocessing of EEG. Basing on the features of EOG in EEG, a EOG removal method from EEG based on HHT is represented. The method combines the statistical properties of natural mode component, and the threshold filtering all modal components. To achieve the purpose of removing EOG from the EEG automatically, all filtered mode components are reconstructed.

A. Principles of Hilbert - Huang transform (Hilbert-Huang Transform, HHT)

Hilbert - Huang transform (HHT) is a time-frequency localization analysis method which is more adaptive than Fourier transform and wavelet transform, which is based on the signal's local characteristics of time scale and defines the instantaneous frequency. It overcomes the shortcoming of the Fourier transform using the global space said for time-varying signal processing. As a new analytical technology, this method, which comes from the signal itself, without the choice of the prior conditions such as basic function, has a good adaptability. Hilbert-Huang Transform consists of two parts, which are empirical mode decomposition (EMD) and Hilbert transform.

The purpose of EMD is to obtain the intrinsic mode functions (IMF) in two following conditions [6]: ① In the entire signal, for one IMF, the number of its extreme points must be equal with that of its crossing points or only one point for their D-value at most; ② At any moment, the average value of the envelope curve at the maximum and the minimum points is zero. That is, the top and down of IMF envelope curve is time-axial symmetrical. There is instantaneous frequency for IMF, which can be obtained by Hilbert transform. But in general, the signal is complex, which does not meet the IMF requirements, therefore the instantaneous frequency can not be obtained. Norden E Huang et al put forward a hypothesis creatively; any complex signal can be comprised by some different, simple IMF components with non-sinusoidal functions; all IMF overlay together for a complex signal. Norden E Huang et al presented EMD based on this assumption [5].

$$X(t) = \sum_{i=1}^{n} c_i(t) + r(t) \tag{1}$$

Where, n is the number of IMF components. EMD algorithm is the key to HHT transform; the decomposition has two main functions: The first is to remove the stack wave, and the second is to make the waveform more symmetrical. The flow of EMD algorithm is shown in Fig. 2.

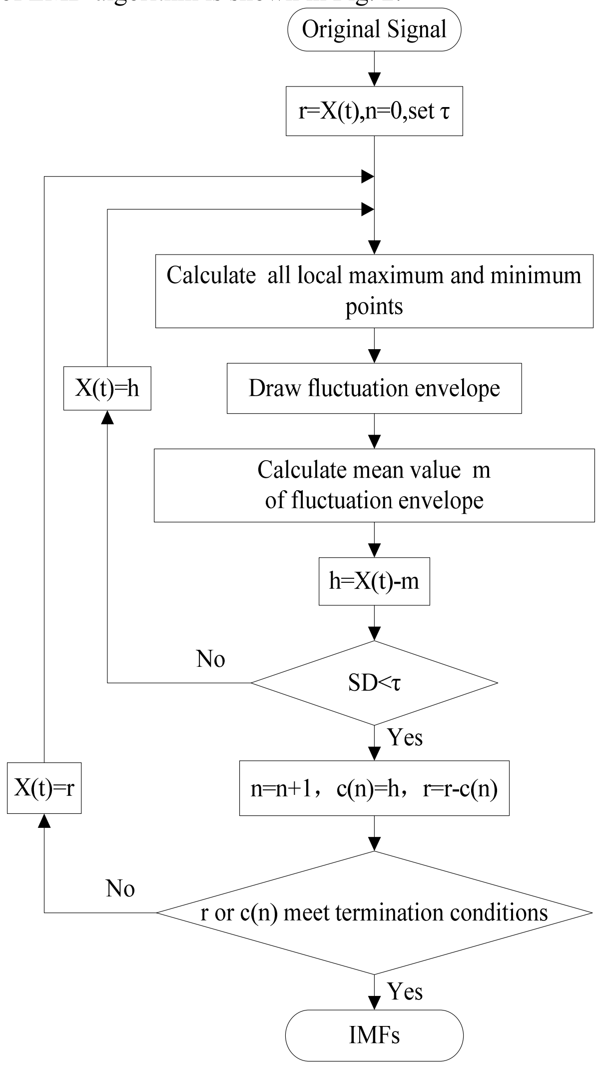

Fig. 2 EMD algorithm flow chart

Where, SD is defined as two standard consecutive deviation between the two results in continuous processing,

$$SD = \sum_{t=0}^{T} \frac{(h_{(k-1)}(t) - h_k(t))^2}{h^2{}_{(k-1)}(t)} \quad (2)$$

Each order of IMF components can be obtained by the EMD method, then are transformed by Hilbert transform, and the instantaneous frequency of each IMF component can be obtained. A new time-frequency methods can obtained by integrating all the instantaneous frequencys, which is called Hilbert spectrum.

Hilbert transform is a linear transformation, and it emphasizes the local quality. The instantaneous frequency deriving from Hibert is the best definition. Hilbert transform can be defined as follows: For any time series X (t), its Hilbert transform Y (t) can be obtained as follows:

$$Y(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{X(\tau)}{t-\tau} d\tau \quad (3)$$

The signal Z (t) can be obtained through X (t) and Y (t):

$$Z(t) = X(t) + iY(t) = a(t)e^{j\theta(t)} \quad (4)$$

$$a(t) = \sqrt{X^2(t) + Y^2(t)} \quad (5)$$

$$\theta(t) = tg^{-1} \frac{Y(t)}{X(t)} \quad (6)$$

By (5) and (6), the instantaneous amplitude and phase can be obtained. Based on (6), the instantaneous frequency can be defined as follow:

$$f(t) = \frac{1}{2\pi} \bullet \frac{d\theta(t)}{dt} \quad (7)$$

Formula (7) shows that the instantaneous frequency is a function of time. It reveals the energy concentration degree of a time signal in frequency. HHT can make the transformation more successfully when applied in nonlinear and non-stationary signal processing. The EEG signals are usually non-stationary, so HHT is suitable for EEG signal processing.

B. EEG-based HHT eye artifacts removal

EEG signal is a quite weak. The scalp of it is only 50μV, which is vulnerable to be influenced by various types of interferences. Among them, EOG artifacts is an important component. Its amplitude can reach up to 100 mV, and the frequency band of EOG artifacts also covers that of EEG[7,8]. Based on the features of EOG artifacts in EEG, an EOG artifacts removing method basing on HHT is proposed. This method combines the statistical properties of the natural mode component, all resulting natural mode components are threshold filtered; all the filtered mode components are reconstructed in order to achieve the purpose of automatic removing EOG artifacts from the EEG. Specific steps are as follows:

(1) Natural mode decomposition of EEG. EEG signal X (t) is non-stationary signal, through EMD, each order of IMF components $c_i(t)$ and the remainder $r(t)$ are obtained; where, i is the number of IMF components, and the value of i is determined by $X(t)$;

(2) All IMF components $c_i(t)$ decomposed by EMD are transformed by Hilbert, the instantaneous frequency $f_i(t)$ is obtained, Based on which, the signal $g_i(t)$ in the band of EEG is obtained by band-pass filtering as expressed in (8);

$$g_i(t) = \begin{cases} 0 & if \quad f_i(t) > f_h \\ 0 & if \quad f_i(t) < f_l \\ c_i(t) & if \quad other \end{cases} \quad (8)$$

Where, f_l is 1Hz, f_h is 30Hz;

(3) The signal $w_i(t)$ is obtained by the threshold filtering and EOG artifacts removal using threshold function in (9) and threshold filtering function in (11);

$$\tau_i = mean|M_i - m_i| + std|M_i - m_i| \quad (9)$$

there, M_i is the value of every extreme point of the first i IMF component $g_i(t)$; mean stands for averaging, std means the standard deviation; m_i is the mean time of the first i IMF components $g_i(t)$; if assuming the length of time series $g_i(t)$ is N, then

$$m_i = \frac{1}{N} \sum_{t=1}^{N} g_i(t) \quad (10)$$

Threshold function τ_i means the upper limit of $g_i(t)$, use mean m_i as its baseline; On this basis, the threshold filter design function can be designed as follow:

$$w_i(t) = \begin{cases} m_i & if \quad |g_i(t) - m_i| > \tau_i \\ g_i(t) & if \quad |g_i(t) - m_i| \le \tau_i \end{cases} \quad (11)$$

(4) Data reconstruction is carried out using all filtered mode component $w_i(t)$, then puer EEG $Y(t)$ without EOG artifacts is obtained;

$$Y(t) = \sum_{i=1}^{n} w_i(t) \quad (12)$$

All mode components obtained through EEG $X(t)$ is EMD decomposed, and $c_i(t)$ is bandpass filtered and threshold filtered, the $w_i(t)$ signal can be obtained without EOG artifacts. Therefore, all $w_i(t)$ signals can be data reconstructed, a relatively pure EEG $Y(t)$ can be obtained as in shown in Fig. 3.

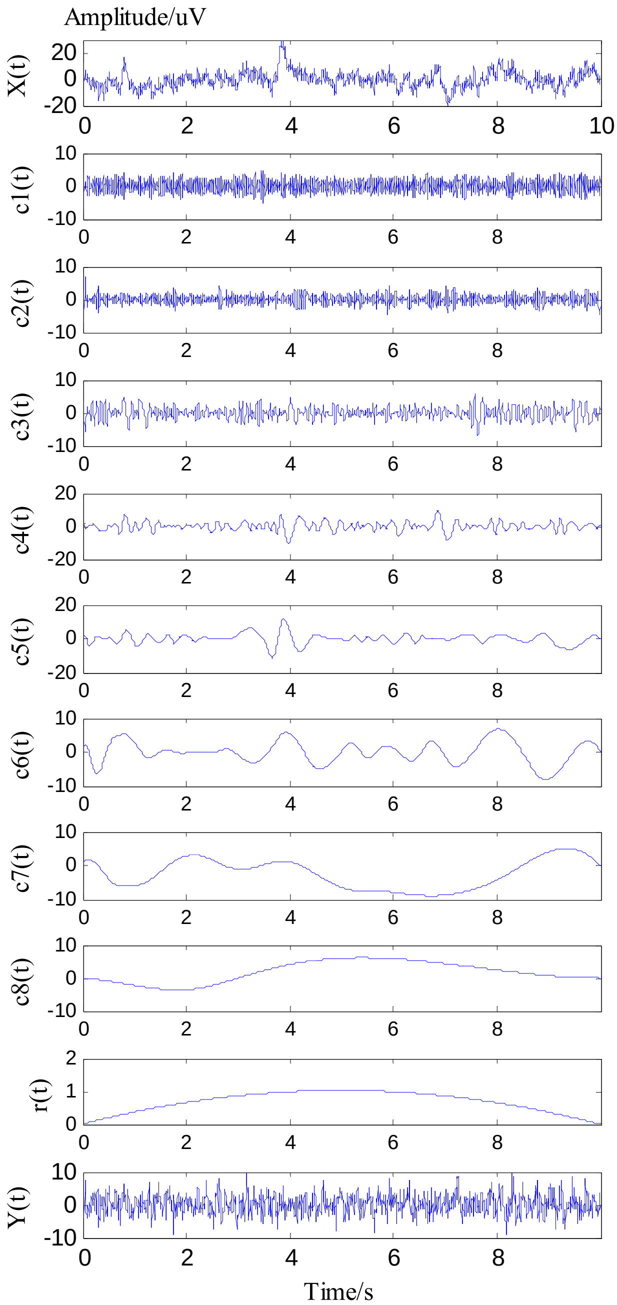

Fig. 3 The resulting empirical mode decomposition components from the original EEG data

IV. EXPERIMENTAL RESULTS AND ANALYSIS

Using the proposed method, as shown in Fig. 4,5,6, and 7, a variety of ocular artifacts are removed, including eye blinks, horizontal eye movement, vertical eye movement, eye rotation etc.

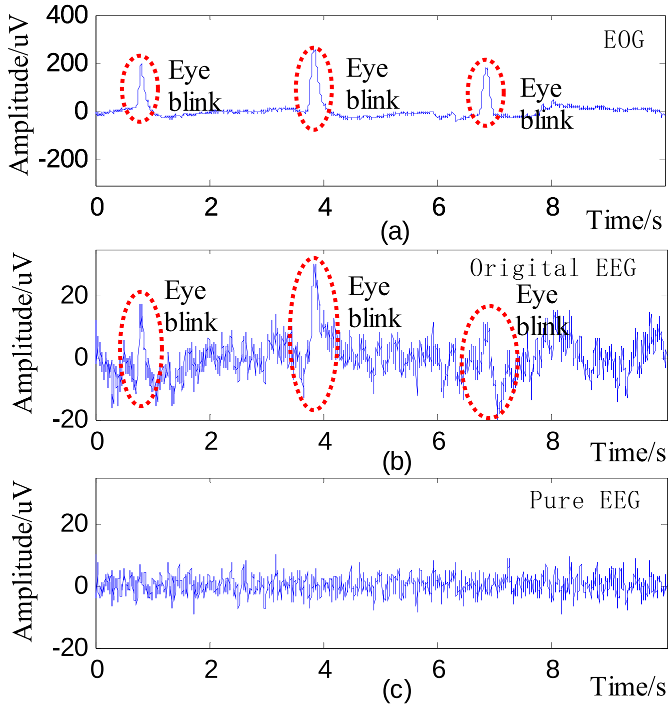

Fig. 4 Eye blink artifacts removal

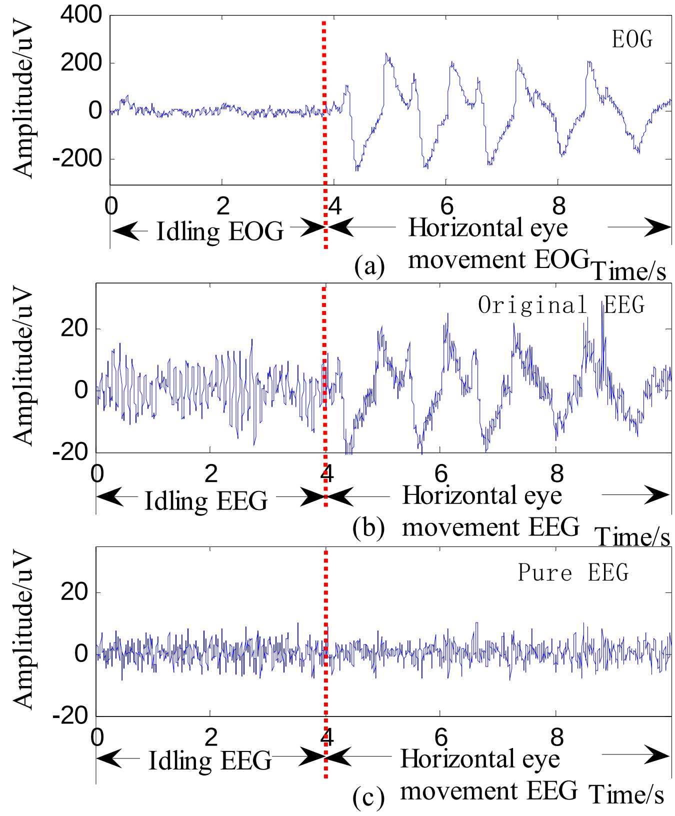

Fig. 5 Horizontal eye movement artifacts removal

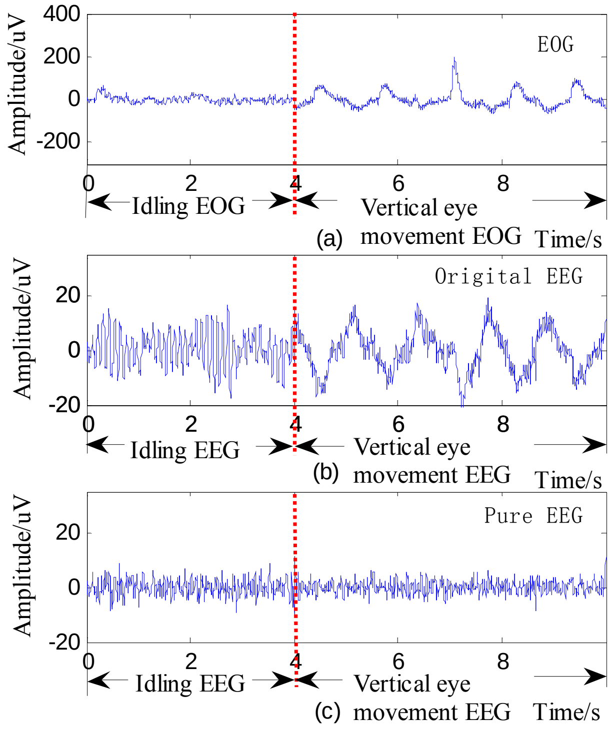

Fig. 6 Vertical eye movement artifacts removal

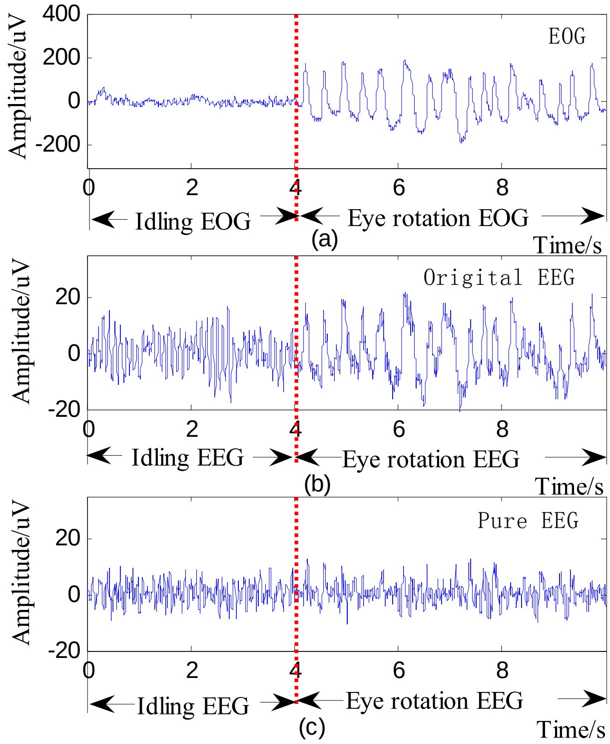

Fig. 7 Rotated eye movement artifacts removal

Compare the method of removing EOG atifacts based on HHT with based on ICA which is widely used in the elimination of EOG artifacts. And Evaluate the effectiveness of the two methods using Relative Root Mean Square Error (RRMSE).

$$RRMSE = \sqrt{\frac{E\|S-\tilde{S}\|^2}{E\|S\|^2}} = \sqrt{\sum_{m=1}^{M}\sum_{n=1}^{N}(S(m,n)-\tilde{S}(m,n))^2 \Big/ \sum_{m=1}^{M}\sum_{n=1}^{N}S(m,n)^2} \tag{13}$$

Where, S is EEG signal uncontaminated by EOG; S' is EEG signal decontaminated; m is the number of signal channel; n is the number of sampling points; RRMSE is able to assess the similarity between the EEG signals uncontaminated and EEG signals decontaminated.

After comparison between the three, such as the EOG signal recorded synchronously, EEG with EOG artifacts removal or not, the HHT based method performs the best in removing the various EOG artifacts (eye blinks, horizontal eye movement, vertical eye movement, eye rotation).The RRMSE is 0.1143 using HHT, but RRMSE is 0.1186 using ICA.

V. CONCLUSIONS

By analyzing the EEG characteristics of EOG artifacts, combining with the statistical properties of natural modal component, a EOG artifacts automatically removing method basing on Hilbert - Huang Transform is presented, it can remove all kinds of EOG artifacts effectively and the original features of EEG can also be reserved as well. Starting from the signal itself, the transform basis function is selected automatically by the data themselves adaptively with a good adaptability and robustness.

Because HHT itself has good local time-frequency characteristics, and it can achieve good aggregation in time-frequency domain and no longer be restricted by Heisenberg uncertainty principle, it is suitable for nonlinear and non-stationary signal processing. Bio-medical signal is a typical non-stationary signal, and HHT will be used more and more widely in that fields.

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